ON THE IDENTIFICATION OF LINES IN THE SOLAR CORONA*

BY D. N. KUNDU

(Received for publication, May 13, 1942)

ABSTRACT. The elements claimed as being present in the solar corona have been examined from a spectroscopist's standpoint. The possibility according to Saha's theory of the solar corona, of the presence of other elements in the neighbourhood of Fe has been studied and the reasons of the absence of many of them have been explained. The presence of Co has been suspected in the corona.

1. INTRODUCTION

The identification of the lines in the solar corona which had long defied the attempts of physicists and astronomers appears at last to have been possible by the brilliant discovery of Grotrian and Edlen that the most intense coronal lines may be ascribed to forbidden transitions of highly stripped iron, nickel and calcium atoms. The details of the identification as far as known at present is given below (Table I).

TABLE I

Lines in the Solar Corona

Wavelength λ	Frequency cm^{-1}	Intensity	Origin	Remarks
3328	30039.46	2.8	—	—
(3359)	29762.24	—	—	—
3388 10	29506.62	44.4	Fe^{+12} ... $3p^2\ {}^3P_2 - {}^1D_2$	Identified by Edlen
3454 13	28942.59	5.6	—	—
(3461)	28885.14	—	—	—
(3505)	28522.54	—	—	—
(3534)	28288.49	—	—	—
3601.00	27762.17	4.4	Ni^{+16} ... $3p\ {}^2P_{\frac{1}{2}} - {}^1P_{\frac{3}{2}}$	Identified by Edlen
(3626)	27570.76	—	—	—
(3641)	27457.18	—	—	—
3642·9	27442.86	—	—	—
(3648)	27404.50	—	—	—
(3651)	27381.98	—	—	—
3800·8	26302.81	—	—	—

* Communicated by Prof. M. N. Saha.

TABLE I (*contd.*)

Wavelength λ	Frequency cm^{-1}	Intensity	Origin	Remarks
3865	25865 91	—	Fe^{+10} ... $3p^4\,{}^3P_1-{}^1D_2$	Bowen obtains a line at λ3871 9, and assigns it to the transition given here.
(3891)	25693.08	—	Fe^{+4} ... $3d^4\,{}^5D_4-{}^3F_4$	(?) *Vide* Text
3986.9	25075.07	.8	—	—
4086.3	24465.13	1.2	—	—
(4130)	24206.27	—	—	—
(4131 4)	24298.06	—	—	—
4231.4	23626.21	3.2	—	—
(4244 8)	23551.62	—	—	—
4311 0	23189.97	—	Ni^{+11} ... $3p^5\,{}^2P_{\frac{3}{2}}-{}^2P_{\frac{1}{2}}$	(?) *Vide* Text
4359.0	22934.61	<.8	Co^{+14} ... $3p\,{}^2P_{\frac{1}{2}}-{}^2P_{\frac{3}{2}}$	Identified by D. Kundu (1941)
(4398)	22731.24	...	—	—
(4533.4)	22054 28	—	-	—
4567.0	21890.09	1.2	—	—
4586	21799.40	—	—	—
(4722)	21171.56	—	—	—
(4725)	21158.12	—	—	—
(4779)	20919.04	—	—	—
(5073)	19706.72	—	—	—
5116 03	19540.98	4.8	—	—
5302.86	18852.52	110	Fe^{+13} ... $3p\,{}^2P_{\frac{1}{2}}-{}^2P_{\frac{3}{2}}$	Discovered in 1868 by Harkness and Young. See further.
5536	18058.58	—	—	—
(5694.0)	17557.48	—	—	—
6374.51	15683.15	28	Fe^{+9} ... $3p^5\,{}^2P_{\frac{3}{2}}-{}^2P_{\frac{1}{2}}$	Discovered in 1914. Identification due to Grotrian.
6704 83	14910.51	3.3	—	Discovered in 1929 by Grotrian.
7059.6	14161 21	4	—	—
7891.94	12676.68	29	Fe^{+10} ... $3p^4\,{}^3P_2-{}^3P_1$	Identified by Grotrian.
8024 2	12458.88	1.3	—	—
10746.8	9314.4	240	Fe^{+12} ... $3p^2\,{}^3P_0-{}^3P_1$	Discovered by Lyot (1934) by means of the Coronagraph. Identified by Edlen.
10797.9	9261.0	150	Fe^{+12} ... $3p^2\,{}^3P_1-{}^3P_2$	,,

The table is taken from Saha[1] with slight modifications. The number of lines in the corona whose existence is admitted by all workers is 22, but, from time to time, other lines have been claimed by various workers. Such lines are shown in round brackets. The intensities are calculated in units of 10^{-6} of the intensity at the same wavelength of the photospheric emission comprised within 1Å.

The exact physical conditions in the solar corona which give rise to these highly stripped atoms have not yet been satisfactorily solved. Attempts were first made by Russell[2] to explain them on a meteor-shower hypothesis but certain experimental facts, for example, the broadening of the lines towards the reversing layer, did not fit in with it. The subject was taken up in more details in an extensive paper by Saha who after a critical review of the whole problem came to the conclusion that some nuclear reaction like uranium fission might be going on in the reversing layer, and the theory worked out on this assumption agrees very well with most of the observed facts. Without concerning ourselves with the explanation of the origin of these highly ionised atoms, we propose to discuss the problem of identification of the coronal lines, which, though partly solved, still needs further elucidation.

2. HOW THE DISCOVERY WAS MADE

From Edlen's data on the spectra of highly stripped atoms, Grotrian noted that the line λ 6374 was given by the difference $^2P_{3/2}-{}^2P_{1/2}$ of the fundamental $2p^5$-state of Fe^{+9} and λ 7892 was given by the difference $^3P_2-{}^3P_1$ of Fe^{+10} ... $3p^4$. With this clue, Edlen tried to trace the origin of the other coronal lines. From his data on lines of stripped Fe-atoms, he identified the other lines as shown above. Russell states that Edlen has been able to ascribe certain other lines to highly stripped atoms of Ni and Ca, but as Edlen's paper has not been available, this has not been shown.

Russell says that 15 out of the 22 well-established lines appear to be due to highly ionised atoms of Fe, Ni and Ca. Apparently none of the other elements Cr, Mn, Co, etc., has been found. From the fact that these elements are prominent also in iron meteorites, Russell appears to throw the suggestion that the coronal lines might be due to large scale meteoric flashes in the outermost atmosphere of the sun, though the subject has not been further pursued.

But spectroscopists are well aware that the absence of the lines of an element may be due to many other causes and mere absence of certain lines does not always indicate the absence of the element in the sources, for the corresponding lines may fall outside the observable region. No one can, thus, make a positive assertion without a critical discussion. For this purpose, a systematic examination of all the available data for tracing out the corresponding lines of neighbouring elements has been undertaken. The results of this investigation are shown in Table II.

TABLE II

Electron configuration ↓	Elements → Difference ↓	Zn	Cu	Ni	Co	Fe	Mn	Cr	V	Ti	Sc	Ca	K
$3p^1$	$^2P_{1/2}-{}^2P_{3/2}$	λ 2546·3	λ 3017	λ 3601	λ 4359	λ 5303	λ 6527	λ 8148	λ 10318	7530 cm^{-1}	5748 cm^{-1}	4307 cm^{-1}	3123 cm^{-1}
$3p^2$	$^3P_1-{}^1D_2$	—	—	—	—	—	—	—	—	—	—	λ 4938.6	λ 5603
	$^3P_2-{}^1D_2$	—	—	—	—	λ 3388.10	—	—	—	—	—	—	—
	$^3P_0-{}^3P_1$	—	—	—	—	λ 10746.8	—	—	—	—	—	—	—
	$^3P_1-{}^3P_2$	—	—	—	—	λ 10797·9	—	—	—	—	—	—	—
$3p^3$	$^4S_{3/2}-{}^2D_{3/2}$	—	—	—	—	—	—	—	—	—	—	λ 3702.6	λ 4165.4
	$^2P_{1/2}-{}^2D_{5/2}$	—	—	—	—	—	—	-	—	—	—	λ 5587	λ 6316
	$^2D_{3/2}-{}^2P_{3/2}$	—	—	—	—	—	—	—	—	—	—	λ 5459·7	λ 6423
	$^4S_{3/2}-{}^2D_{5/2}$	—	—	—	—	—	—	—	—	—	—	λ 3646.3	λ 4124.5
$3p^4$	$^3P_2-{}^1D_2$	—	—	—	—	λ 2596.6	λ 2918 8	λ 3273	λ 3686	λ 4144 6	λ 4672	λ 5309	λ 6101
	$^3P_1-{}^1D_2$	—	—	—	—	λ 3872	λ 4122.4	λ 4407·9	λ 4733	λ 5105 8	λ 5539.4	λ 6085 8	λ 6794.8
	$^3P_2-{}^3P_1$	λ 3862	λ 4424	λ 5234	λ 6335	λ 7892	λ 9997	7860 cm^{-1}	6000 cm^{-1}	4540 cm^{-1}	3350 cm^{-1}	2404 cm^{-1}	1673 cm^{-1}
	$^3P_1-{}^3P_0$	—	—	—	—	1760 cm^{-1}	1740 cm^{-1}	1740 cm^{-1}?	1580 cm^{-1}	1360 cm^{-1}	1126 cm^{-1}	862 cm^{-1}	641 cm^{-1}
$3p^5$	$^2P_{3/2}-{}^2P_{1/2}$	λ 3104.6	λ 3662	λ 4314	λ 5185	λ 6374	λ 7949	λ 10053	7657 cm^{-1}	5825 cm^{-1}	4328 cm^{-1}	3124 cm^{-1}	2165 cm^{-1}

3. METHOD OF CALCULATION

The $3p[{}^2P_{1/2} - {}^2P_{3/2}]$ *lines.*

The elements range from Zn^{+17} to K^{+6} having Al-like structure. The data for these isoelectronic elements were available for Al, Si^{+1}, P^{+2}, ... Sc^{+8} from various workers, a valuable guide in this search being provided by the extensive bibliography given by Boyce[3] on atomic spectra in the vacuum ultra-violet. The values for Fe and Ni were taken on the assumption that Edlen's identification of the line λ 5302.86 from Fe^{+13} and λ 3601.00 from Ni^{+15} was valid. We know that

$$\Delta\nu[3p^2P_{\frac{1}{2}} - 3p^2P_{\frac{3}{2}}] = \frac{R\alpha^2(Z-\sigma)^4}{n^3 l(l+1)}$$

where

R = Rydberg constant,
α = Sommerfeld's fine-structure constant,
Z = atomic number,
σ = screening factor,
n = principal quantum number,

and l = azimuthal quantum number.

The screening factor σ was calculated for the known atoms by using the above formula (Table III). The values of σ were plotted against atomic number (Graph 1) and σ for the unknown elements Zn, Cu, Co, Mn, Cr, V, and Ti found

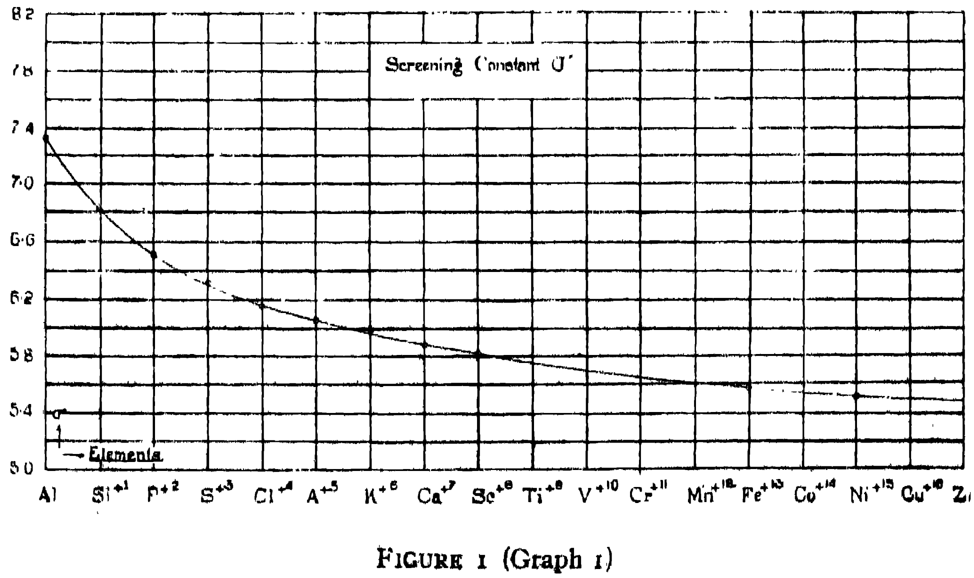

FIGURE 1 (Graph 1)

from the curve by interpolation and extrapolation. The $\Delta\nu$'s were then calculated by using the above relation.

The $3p^2$-lines.

The elements included are from Zn^{+16} to K^{+5}. The data for these Si-like atoms were available only up to K^{+5} and Ca^{+6} (Robinson[4]). So no extrapolation was attempted as this leads to large error when the elements are very far removed from each other.

TABLE III

$\Delta\nu[3p^2P_{\frac{1}{2}} - 3p^2P_{\frac{3}{2}}]$ and Screening factor σ

Element $1s^2.2s^2.2p^6.3s^2\,3p$.	$\Delta\nu$ (obs.)	σ (calc.)	Reference
Al	112.07	7.326	Saha, *Mod. Phys.*, 1, 571.
Si^{+1}	287	6.82	,,
P^{+2}	559.5	6.519	,,
S^{+3}	950.2	6.318	,,
Cl^{+4}	1500	6.147	,,
A^{+5}	2210	6.05	Parker & Phillips, *Phys. Rev.*, **58**, 93, (1940).
K^{+6}	3123	5.97	Whitford, *Phys. Rev.*, **46**, 793, (1934).
Ca^{+7}	4307	5.87	,,
Sc^{+8}	5748	5.82	Kruger & Phillips, *Phys. Rev.*, **52**, 97 (1937).
Ti^{+9}	—	—	
V^{+10}	—	—	
Cr^{+11}	—	—	
Mn^{+12}	—	—	
Fe^{+13}	18853	5.57	Edlen
Co^{+14}	—	—	
Ni^{+15}	27762.4	5.50	Edlen

The $3p^3$-configuration.

The elements run from Zn^{+15} to K^{+4} and have P-like structure. The data are available only up to K^{+4} and Ca^{+5} (Bowen[5]). So extrapolation was not practicable. Now, it will be found from Table I that iron atoms having $3p$, $3p^2$, $3p^4$ and $3p^5$ electronic structure have all been found in the corona but no $3p^3$-lines. But this cannot be used as an argument that Fe^{+12} is absent in the corona, for since Fe^{+11} and Fe^{+13} are present, Fe^{+12} must be present. The data for the $3p^3$-atoms being insufficient, an attempt was made to study how

$$^4S_{3/2} - {}^2D_{3/2},\ {}^2P_{3/2} - {}^2D_{5/2}, \ldots$$

differences progress from element to element with $2p^3$-configuration. But there too the available data were too meagre for the purpose.

$3p^4$-configuration.

The elements range from Zn^{+14} to K^{+3}. Reliable data were available up to Fe^{+10} (Table IV). On tabulating the data, it was found that the lines for the $^3P_2 - {}^1D_2$ and $^3P_1 - {}^1D_2$ differences had already become so short that it was not necessary to extrapolate up to Zn for them. The $^3P_1 - {}^3P_0$ differences again would give lines too far in the infra-red. The lines for the $^3P_2 - {}^3P_1$ differences alone were in the observable region. The log $\Delta\nu$'s for these S-like elements

TABLE IV

$3p^4$ — lines

Ion $1s^2.2s^2.2p^6.3s^2.3p^4$	$^3P_2 - {}^3P_1$	$^1D_2 - {}^3P_1$	$^3P_2 - {}^1D_2$	$^3P_1 - {}^3P_0$	Reference
S	398	—	—	—	Bacher & Goudsmit, *At. Energy States*, p. 397.
Cl^{+1}	694	—	—	—	,, p. 140.
A^{+2}	1112.4	12888	—	—	Boyce, *Phys. Rev.*, **48**, 096.
K^{+3}	1673	14713	16386	641	Bowen, *Phys. Rev.*, **46**, 791.
Ca^{+4}	2404	16427	18831	862	,,
Sc^{+5}	3350	18047	21397	1126	Kruger & Pattin, *Phys. Rev.*, **52**, 621.
Ti^{+6}	4540	19580	24120	1360	Edlen, *Z. fur Phys.*, **204**, 190.
V^{+7}	6000	21120	27120	1580	,,
Cr^{+8}	7860	22680	30540	1740	,,
Mn^{+9}	10.000	24250	34250	1700	,,
Fe^{+10}	12680	25820	38500	1760	,,

up to Fe^{+10} were plotted against the atomic numbers and the wavelengths for Co, Ni, Cu, and Zn were obtained by extrapolation (Graph 2).

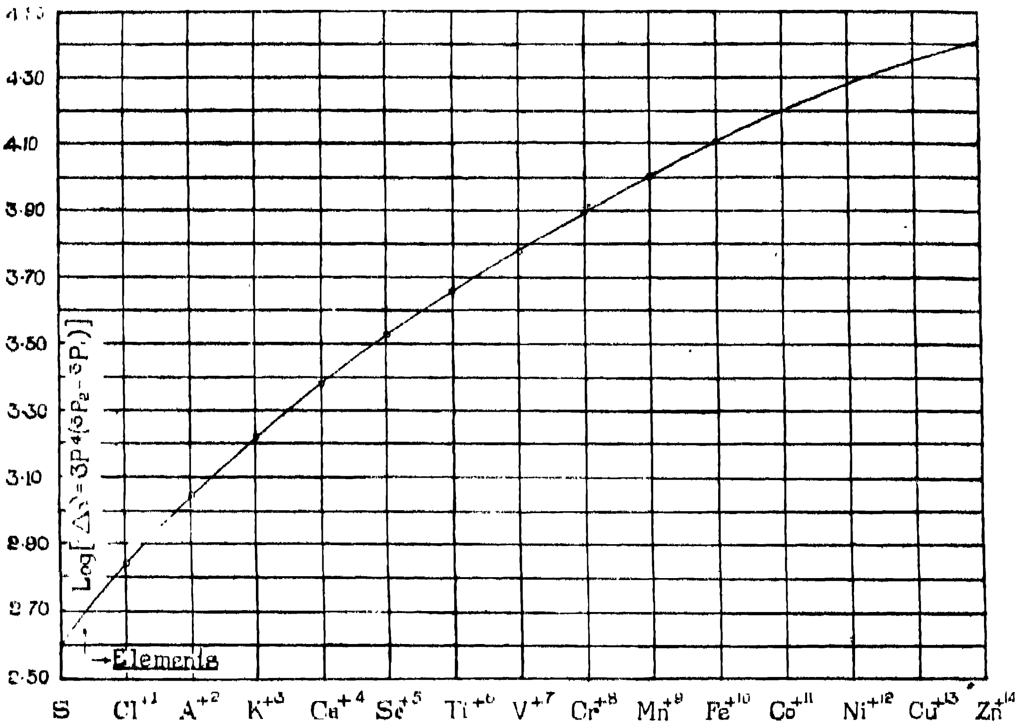

FIGURE 2 (Graph 2)

The $3p^5[^2P_{\frac{1}{2}} - {}^2P_{\frac{3}{2}}]$ *lines.*

The elements run from Zn^{+13} to K^{+2}. These elements are isoelectronic with Cl. Data were available up to Co (Table V). The lines for Ni, Cu and Zn

TABLE V

$3p^5$ – lines

Ion $1s^2.2s^2\ 2p^6.3s^2.3p^5$	$^2P_{3/2} - {}^2P_{1/2}$ ν	Reference
Cl	883	Bowen, *Phys. Rev*, **31**, 497.
A^{+1}	1433	,,
K^{+2}	2165	,,
Ca^{+3}	3124	,,
Sc^{+4}	4328	Kruger & Phillips, *Phys. Rev.*, **51**, 1087.
Ti^{+5}	5825	,,
V^{+6}	7657	,,
Cr^{+7}	9947	,,
Mn^{+8}	12576	,,
Fe^{+9}	15690	Edlen, *Z. fur Phys.* **104**, 407.
Co^{+10}	19280	,,

were obtained by plotting log $\Delta\nu$ against atomic number as before and extrapolating the curve (Graph 3).

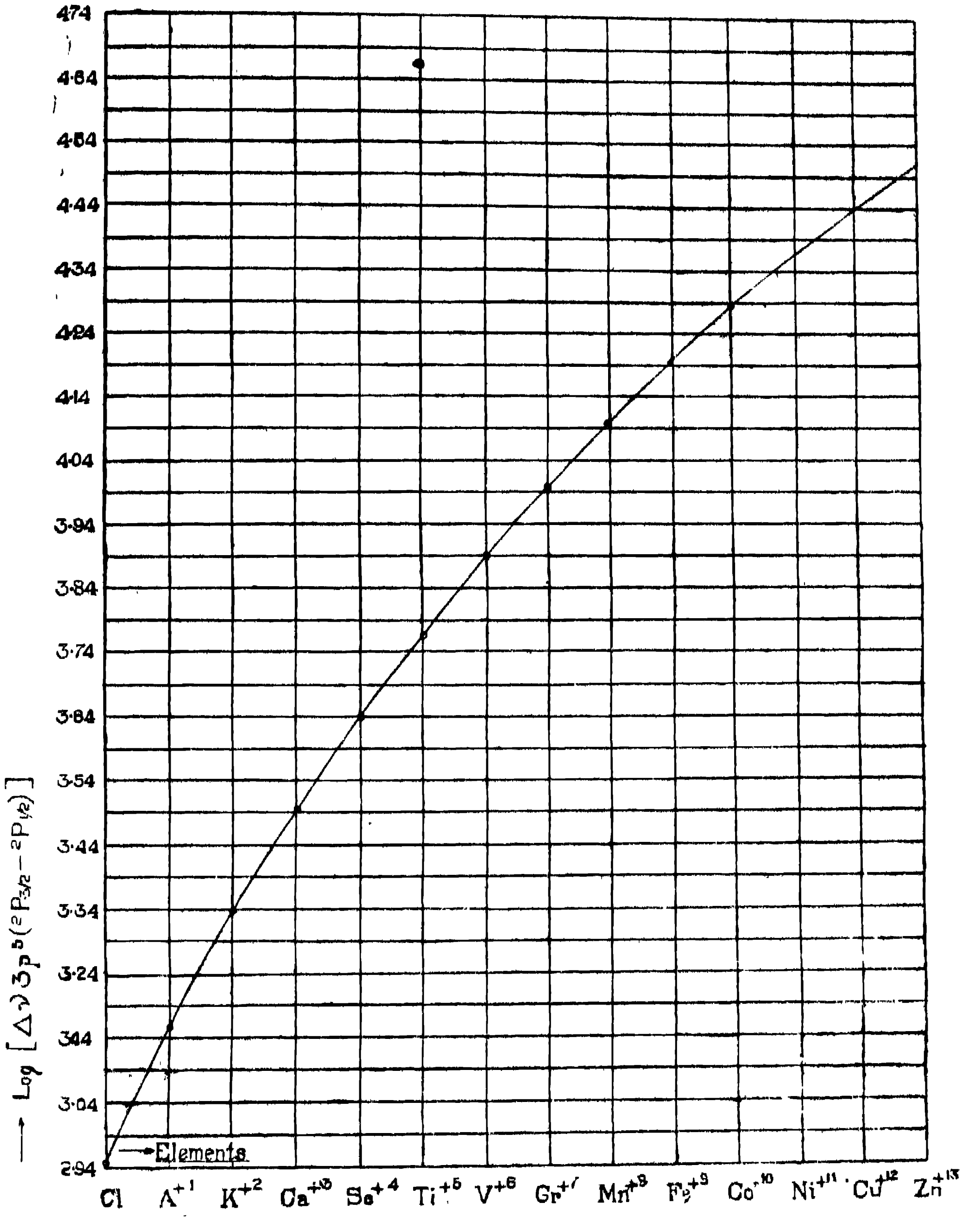

FIGURE 3 (Graph 3)

4. DISCUSSION

The lines identified by Grotrian and Edlen are mostly due to $3p^x$-combinations of Fe and Ni and two lines due to $2p^x$-combinations of Ca. The data for the $2p^x$-sequence being insufficient for extrapolation up to Ca, we have studied only the $3p^x$-configurations of elements in the neighbourhood of Fe.

As has already been pointed out, the $3p$, $3p^2$, $3p^4$ and $3p^5$ lines of Fe have been observed in the corona. The absence of $3p^3$ which on Saha's theory, must also be occurring, is easily seen to be due to the fact that the wave-lengths diminish very rapidly for the $3p^3$-combinations and for Fe and Ni the lines would be too short to be observed. The line λ 3872 is interesting in that Bowen[6] has observed that this single line due to $3p^4\ {}^3P_2 - {}^3P_1$ comes in the spectra of nebulae N G C 7027, 7662. The coronal line λ 3865 whose wave-length is very uncertain may be due to this transition.

Presence of other elements.

Since the exact theory of a three-fold fission of the type assumed by Prof. Saha has not yet been rigorously worked out, we do not know exactly the masses of the fragmentary nuclei. Assuming, therefore, that the theory is substantially correct, one may justifiably look for the presence of elements close to Fe and Ni, for example, Cu, Co, Mn, Cr, V, Ti,...etc. If they occur, the strongest lines will be due to $3p\ {}^2P_{1/2} - {}^2P_{3/2}$, $3p^5\ {}^2P_{3/2} - {}^2P_{1/2}$. The probable position of these lines is shown in Table II. We find that the $3p\ {}^2P_{1/2} - {}^2P_{3/2}$ -combination gives us lines which cannot be traced beyond Ni, as they lie in the short wave-length side of λ 3000 (for Cu it is λ 3017). For Co we have a line λ 4359 tentatively identified by the author [7]. If Co occurs at all, this line would come first as in the case of the line λ 5303 of Fe. The Mn-line is λ 6527 and we do not have yet any such line in the corona. The lines for Cr^{+11}, λ 8148 and V^{+10}, λ 10318 may be looked for in the infra-red. Though Lyot[8], by his excellant coronagraph, has succeeded in photographing the coronal lines in board day-light up to λ 10800, yet by this method only the intense lines can be studied. The investigation of this region during total eclipses is thus still an useful work for settling the problem of the corona. Ti, Sc.......are too far in the infra-red.

Turning to the $3p^5\ {}^2P_{3/2} - {}^2P_{1/2}$ lines, we cannot go beyond Cu. The copper line is λ 3662 and there is a number of doubtful lines here, *e.g.*, λ 3648 and λ 3651. The accuracy in the measurement of the wave-lengths of the faint coronal lines is very small for, owing to the short duration of the totality of the eclipse, the spectrographs have necessarily to be of low dispersion and high light-gathering power so as to enable the fainter lines to be photographed. The line λ 5185 for Co^{+10} appears to be absent on the strength of Edlen's data. The case of Ni is more favourable in that Ni^{+11} gives the line λ 4314 which agrees fairly well with λ 4311 in the corona. The method followed was not capable of a greater accuracy. The Mn-line is at λ 7949 and the Cr-line at λ 10053 for which search may be made. The line of Zn provisionally put at λ 3105 is more uncertain. We see, therefore, that no other element than Co possesses for its identification such advantages as are enjoyed by Fe and Ni.

5. OTHER ELECTRONIC CONFIGURATIONS OF Fe

If the theory of Prof. Saha be correct, then not only atoms having np^x configurations will be found in the corona but also atoms having nd^x, etc., electron-structures ; for the highly stripped atom after being formed will in course of its upward flight go on capturing electrons one after another and provided the ion originated at a sufficiently low level, we shall get all the electronic configurations until we get a neutral atom. The data for the other elements Ni, Co, and Ca found in the corona being insufficient, and iron being by far the most important element traced in the corona, we confine ourselves to the latter only and examine its other configurations.

Fe^{+x}, for $x=1$ to 6, all have metastable states and their forbidden lines have been found to occur in many novae and stars, *e.g.*, Fe^{+1} in η-Carinae[8], Fe^{+5} in Nova Pictoris, Fe^{+4}...Fe^{+6} in nebulae N G C 7027, 7662 [6]. $x=1$ to 3 ($3d^6 4s$, $3d^6$, $3d^5$) have not yet been found in the corona. The case of Fe^{+4} is interesting that it is found in nebulae N G C 7027 and 7662[6], and almost all of the lines which are strongest in these nebulae appear to be present in the corona as very weak lines, as will be evident from a comparison of Table I with Bowen's chart[6] for $Fe^{+4}...3d^4$ atom. The line λ 3891 [$Fe^{+4}...3d^4\ {}^5D_1 - {}^3F_4$] which is very strong in the nebulae appears to be definitely present in the corona as a faint line. $Fe^{+15}...3d^3$ and $Fe^{+6}...3d^2$ are found to be absent. $Fe^{+7}...3d$ has no metastable state. The $3p^x$, $x=1,..,6$ have all been found with the exception of $x=3$, in which case though there are four metastable states, yet the transitions give lines too far in the ultra-violet to be observed in the corona. $Fe^{+14}...3s^2$, $Fe^{+15}...3s$, $Fe^{+16}...2p^6$ have no metastable states. The higher ionised atoms have not yet been spectroscopically studied.

6. CONCLUSION

Considering the inaccuracy in the measurement of the coronal lines except the strongest ones, it is very difficult to try to identify the lines and trace them to known ions. If according to Prof. Saha's ideas, Fe or some other neighbouring atoms are produced, an examination of Table II will show that many of these atoms will remain undetected by virtue of their spectra falling outside the accessible range of wave-lengths. The extrapolation method is at best only tentative, no exact prediction being possible until these ions are experimentally investigated. Even in the latter case there is the unavoidable error involved in calculating visible lines from data in the X-ray region.

My grateful thanks are due to Prof M. N. Saha, D.Sc., F R.S., for his

kindly checking the extrapolation curves and for his kind interest and helpful discussions.

PALIT LABORATORY OF PHYSICS,
UNIVERSITY COLLEGE OF SCIENCE,
CALCUTTA.

REFERENCES

[1] Saha, M. N., *Proc. Nat. Inst. Sc. India*, **8**, 99 (1942).
[2] Russell *Scien. American*, August (1941).
[3] Boyce, J. C., *Rev. Mod. Phys.*, **13**, 1 (1941).
[4] Robinson *Phys. Rev.*, **52**, 724 (1937).
[5] Bowen, *Phys. Rev.*, **46**, 793 (1934).
[6] Bowen, I. S., *Lick Observatory Bull.*, No. 495.
[7] Kundu, D. N., *Science and Culture*, **7**, 364 (1942)
[8] Merrill, P. W., *Astro.Phys. Jour.*, **67**, 391 (1928).
[9] Jones, H. G., *M. N. R. A. S.*, **92**, 728 (1932).